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ABSTRACT (Maximum 200 words)

The first goal of this project is to determine the effects of plastically induced microstresses on fatigue crack propagation in steel. To accomplish this specimens and heat treatment have been designed, the specimens have been deformed to introduce different microstress states, and the microstresses measured using neutron diffraction. Neutron measurements of the stresses in the cementite phase were successful and confirm that only microstresses are produced by the plastic deformation. Initial results from the neutron measurements of the microstresses indicate that there is some asymmetry in the magnitude of the stresses introduced by tensile and compressive deformations. This effect is probably due to pre-existing thermal residual microstresses between the phases. Fatigue crack propagation tests are now being performed.

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Summary

The first goal of this project is to determine the effects of plastically induced microstresses on fatigue crack propagation in steel. To accomplish this specimens and heat treatment have been designed, the specimens have been deformed to introduce different microstress states, and the microstresses measured using neutron diffraction. Neutron measurements of the stresses in the cementite phase were successful and confirm that only microstresses are produced by the plastic deformation. Initial results from the neutron measurements of the microstresses indicate that there is some asymmetry in the magnitude of the stresses introduced by tensile and compressive deformations. This effect is probably due to pre-existing thermal residual microstresses between the phases. Fatigue crack propagation tests are now being performed.

1.0 Introduction

Residual stresses have long been known to affect material behavior. Fatigue failure, for example can be accelerated or inhibited by the presence of residual stresses. What has traditionally been thought of as residual stresses would, more specifically, be termed macrostresses. More recently, microstresses, or stresses existing between the phases in two-phase or composite materials have become of interest. Microstresses have been shown to affect the properties of a two phase material, for example producing strength differential and Bauchinger effects in aluminum matrix composites [1,2]. In this project the roles of macrostresses and microstresses are to be studied in the fatigue behavior of steel. The work at the University of Missouri will be coordinated with another project at Northwestern University.

2.0 Specimen design

1080 steel was selected to give a large volume fraction of cementite in a technologically relevant material. A large volume fraction of cementite is necessary to facilitate diffraction measurement of the microstresses in that phase for both neutron and companion x-ray measurements to be performed by Northwestern University. A spheroidized microstructure was adopted to facilitate a simple model of randomly arranged spherical particles in a matrix. Heat treatment consisted of austenitizing at 800°C for 30 minutes followed by quenching in water. The specimens were then spheroidized at 700°C for 3 hours. This produced a mean particle size of 0.4 μm. A relatively small particle size was needed to facilitate the measurement of stresses in the cementite phase near a crack tip using a small x-ray beam. In the irradiated volume of a 10 μm diameter x-ray beam there should be about 3600 cementite particles which should be sufficient for obtaining a good diffraction pattern and hence valid stress results.

Specimens were designed to have a gage section which could be given a uniform plastic deformation from which a compact tension specimen could then be cut. The deformation will introduce a uniform microstress field through the gage section through which a crack can be grown from the compact tension specimen. Original specimen dimensions are shown in Figure 1 along with the dimensions of the compact tension specimens cut from the gage section. The specimens were deformed to +2, +1, 0, -1, and -2% plastic strain. Since the ferrite phase plastically deforms while the cementite phase does not, residual microstresses develop between the two phases after plastic deformation of the specimens.

3.0 Neutron stress measurement of microstresses

After deformation, the grip ends of the specimens were cut off and the microstresses measured with neutron diffraction. Neutron measurements were performed on the MURR 2XD powder diffractometer utilizing a position sensitive detector (PSD) [3]. The neutron wavelength was 1.478 Å. The incident beam slits were set to 8 x 5 mm and the diffracted beam was defined for the PSD by an oscillating radial collimator.

The diffraction pattern for the steel over the range 69 to 89°2θ is shown in Figure 2. The 211 peak was used for stress measurements in the ferrite phase. In the 2θ range of interest, there were no isolated diffraction peaks in the cementite phase. Thus two clusters of peaks (the 004/152/303/060 peaks at $2\theta \approx 81°$ and the 430/104/143 peaks at $2\theta \approx 83°$) were used to determine the stresses in this phase. The diffraction elastic constants $S_1 = -1.26 \times 10^{-6}$ MPa^{-1} and $S_2/2 = 4.97 \times 10^{-6}$ MPa^{-1} were used for the ferrite phase while $S_1 = -1.29 \times 10^{-6}$ MPa^{-1} and $S_2/2 = 4.91 \times 10^{-6}$ MPa^{-1} were used for the cementite phase. These values were taken from Reference 4.

Initial measurements were performed on specimen T2 which was initially deformed by 2% in tension. Diffraction peaks were measured with ψ-tilts between 0 and 90°. Plots of d vs. $\sin^2\psi$ are shown in Figures 3-5 and are nicely linear. The slope of these plots give the quantity σ_{11}-σ_{33}, where σ_{11} is defined as the stress along the plastic deformation direction and σ_{33} is the stress perpendicular tot he deformation direction. It is assumed, because of the uniaxial deformation, that σ_{22}, also perpendicular to the deformation direction is equal to σ_{33}. The values of σ_{11} and σ_{33} cannot be determined individually without precisely measuring the stress-free lattice spacings of the ferrite and cementite phases [4] which proves difficult with neutron diffraction. However, the changes in stress from the undeformed state, $\Delta\sigma_{11}$ and $\Delta\sigma_{33}$ can be determined without stress-free specimens. From the data shown in Figures 3-5 the stress quantity σ_{11}-σ_{33} in the ferrite phase is computed to be -163 MPa. The quantity σ_{11}-σ_{33} in the cementite phase is 1320 MPa using the 004/152/303/060 peak and 900 MPa using the 430/104/143 peak. These are the total stress in their respective phases and, in general, could be the sum of the macrostress and microstresses present. Because the specimens received a uniform macroscopic plastic deformation, one would expect the macrostress component to be zero. Using the definitions of the total stresses measured in each phase and the equation of stress equilibrium for microstresses in a two-phase material [5],

$$ {}^{t}\sigma^{\alpha}_{ij} = {}^{M}\sigma_{ij} + {}^{\mu}\sigma^{\alpha}_{ij} \tag{1} $$

$$ {}^{t}\sigma^{\beta}_{ij} = {}^{M}\sigma_{ij} + {}^{\mu}\sigma^{\beta}_{ij} \tag{2} $$

$$ {}^{\mu}\sigma^{\alpha}_{ij} + {}^{\mu}\sigma^{\beta}_{ij} = 0 \tag{3} $$

one can separate the measured stresses into a macrostress and the microstress in each phase. For specimen T2 this gives macrostresses of ${}^{M}\sigma_{11}$ - ${}^{M}\sigma_{33}$= -3 MPa which is negligible and confirms the assumption of no macrostress being generated from the uniform plastic deformation.

The cementite phase gives very weak diffraction peaks and determining their positions with enough precision to determine stresses is time consuming. The collection of diffraction peaks at six tilts from the cementite phase for specimen T2, for example, took a total of 61 hours while the six ferrite peaks were measured in 1.5 hours. Because the macrostresses were demonstrated to be zero, the microstresses can be determined in both phases with a measurement in only one phase by using the equilibrium equation for microstresses, Equation 3. Therefore, in the remaining specimens, the stresses were measured in the ferrite phase only and the microstresses in the cementite phase were computed using Equation 3. These results are summarized in Table 1.

The changes in stresses normal to the deformation direction, $\Delta\sigma_{11}^{\alpha}$, are compressive after tensile deformation and tensile after compressive deformation, as would be expected [4]. The stress change is larger for tensile deformation than for compressive deformation because in the undeformed state there are thermal stresses present with the ferrite phase being in tension. The stress changes perpendicular to the deformation direction, $\Delta\sigma_{33}^{\alpha}$, all show a decrease in stress except for the 1% compression specimen. The decrease in stress can be explained as a relaxation of the tensile thermal stresses in the ferrite due to deformation perpendicular to this direction. The 1% compression specimen is an exception and seems quite peculiar. The specimen was measured four times and the results are quite reproducible. Further study will be required to explain this result.

4.0 Crack growth measurements

Compact tension specimens have been machined from the specimens and are currently being tested for fatigue crack propagation rates.

References

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Table 1

Microstresses (MPa) in plastically deformed 1080 steel specimens.

	Ferrite Phase		Cementite Phase	
% Deformation	$\Delta\sigma_{11}^{\alpha}$	$\Delta\sigma_{33}^{\alpha}$	$\Delta\sigma_{11}^{c}$	$\Delta\sigma_{33}^{c}$
+2	-358	-189	2400	1260
+1	-336	-126	2250	840
0	0	0	0	0
-1	126	101	-840	-680
-2	67	-121	-450	810

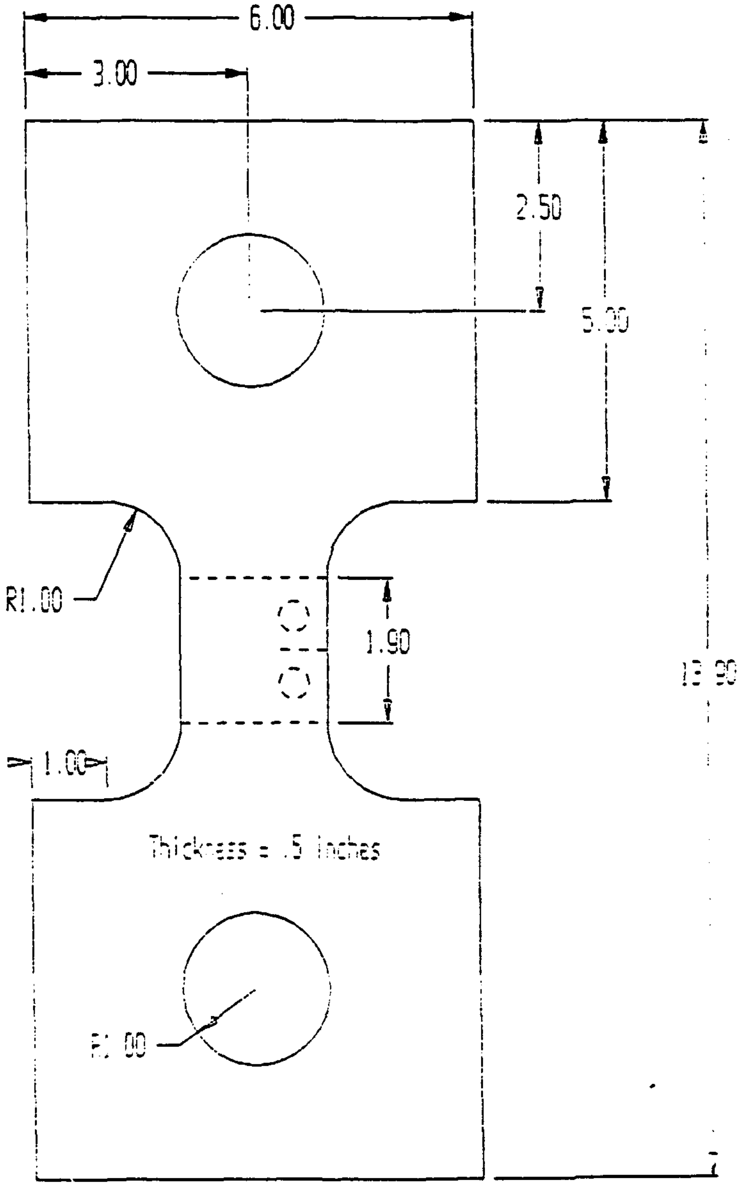

Figure 1. Specimens used to introduce microstresses into 1080 steel, showing location of compact tension specimens machined out of gage section after plastic deformation.

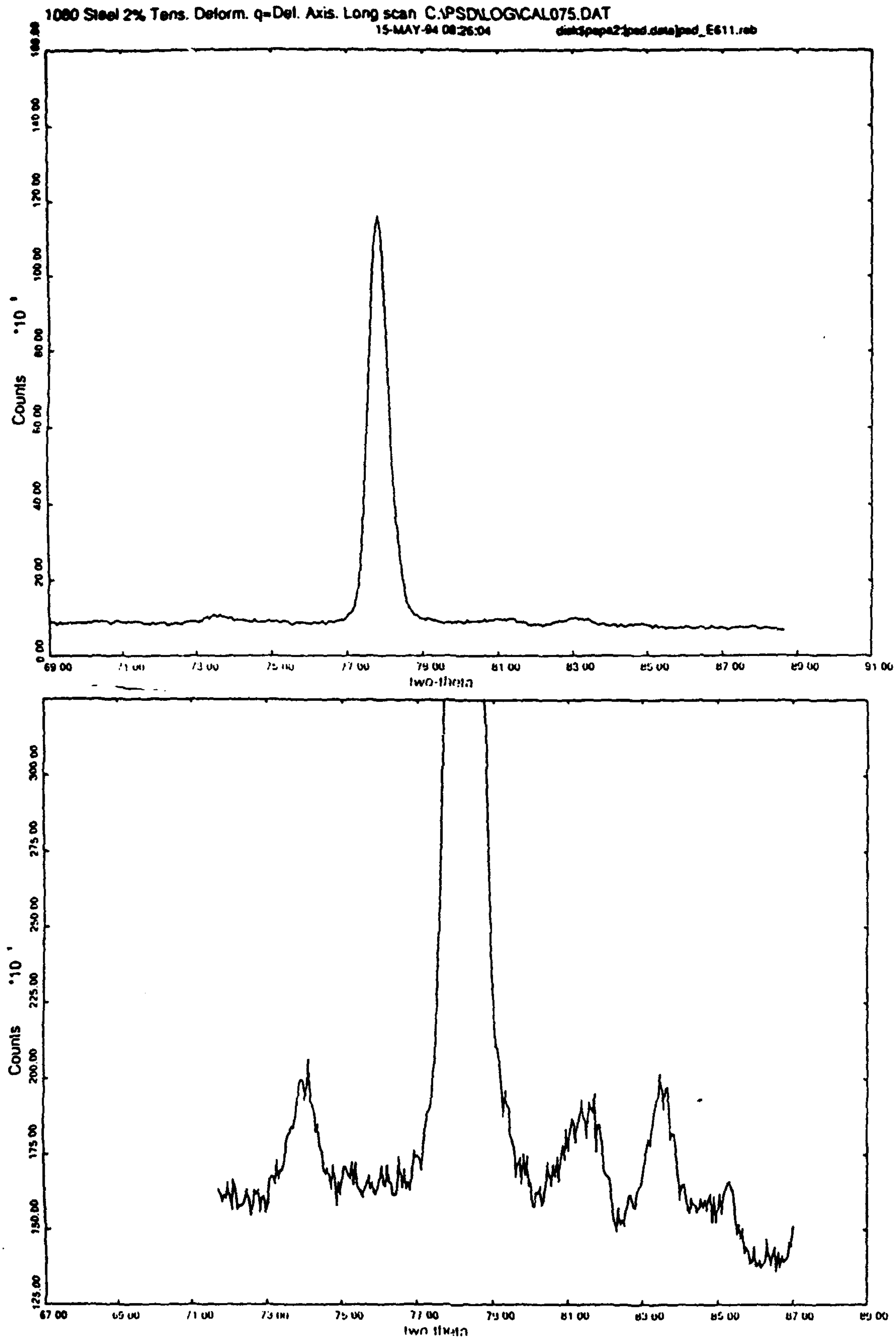

Figure 2. Neutron diffraction pattern from 1080 steel specimens emphasizing (a) the 211 ferrite peak and (b) the cementite peaks.

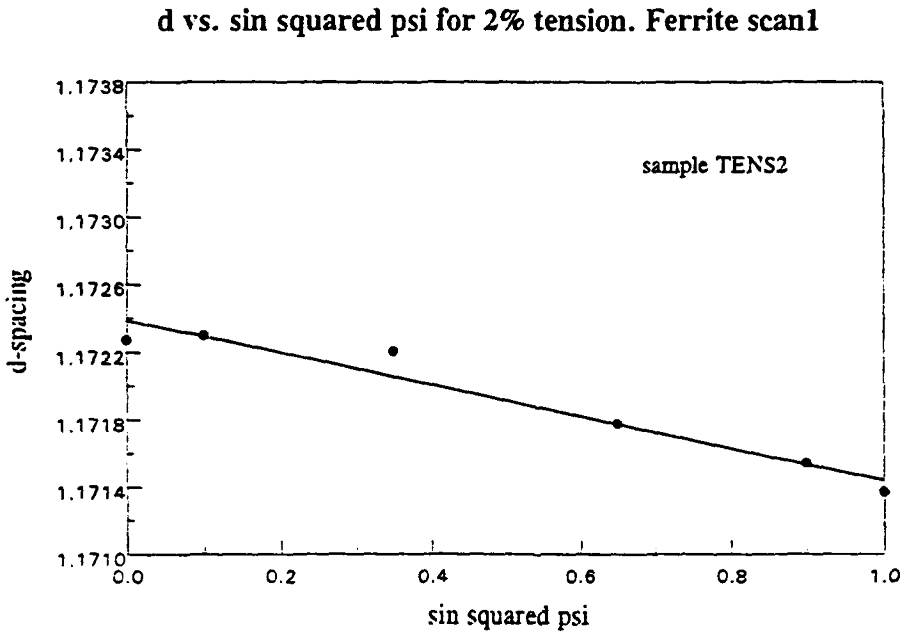

Figure 3. Plot of d vs. $\sin^2\psi$ for the 211 ferrite diffraction peak of specimen deformed 2% in tension.

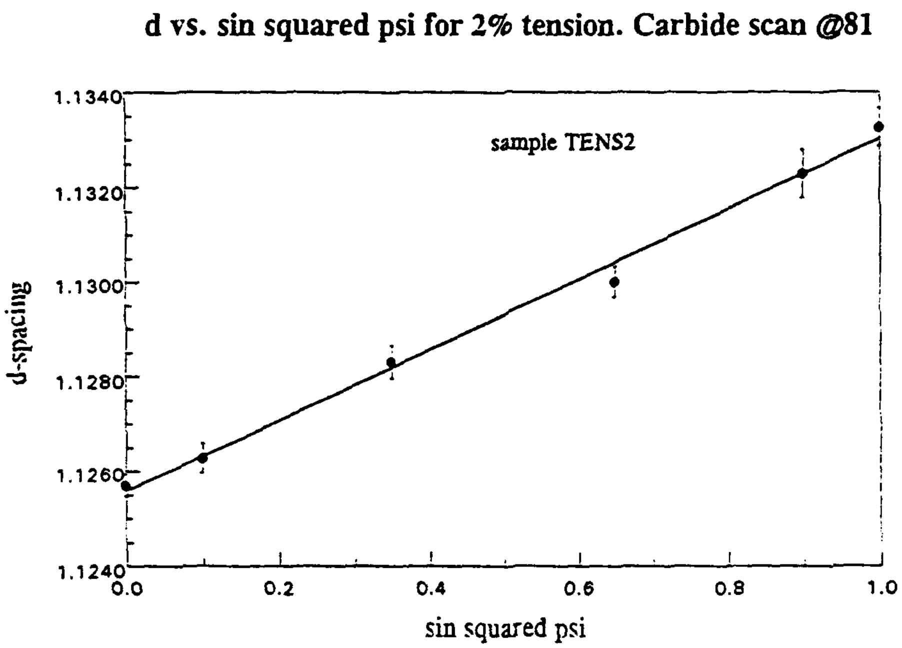

Figure 4. Plot of d vs. $\sin^2\psi$ for the 004/152/303/060 cementite peaks at $2\theta=81°$ for specimen deformed 2% in tension.

d vs. sin squared psi for 2% tension. Carbide scan @83

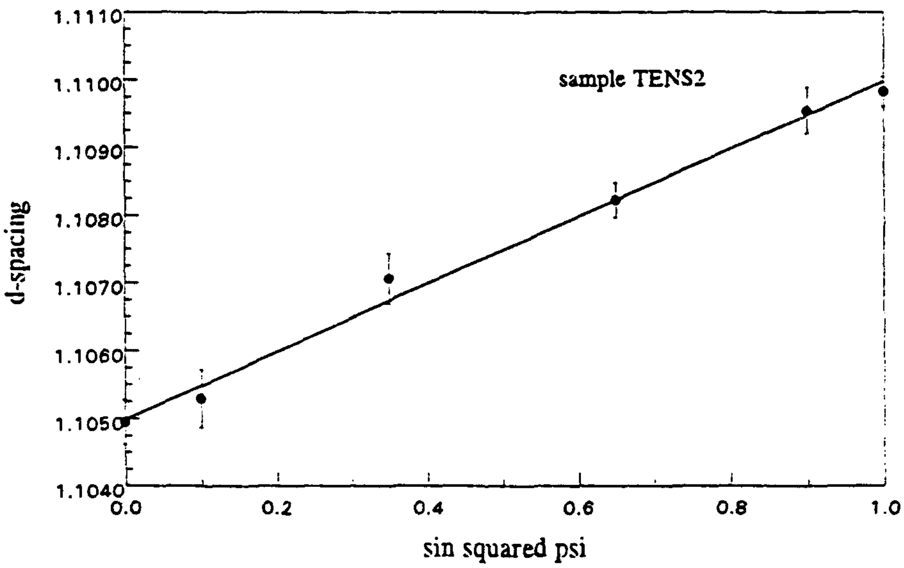

Figure 5. Plot of d vs. $\sin^2\psi$ for the 430/104/143 cementite peaks at $2\theta=83°$ for specimen deformed 2% in tension.